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(54) **JET IMPINGEMENT COOLING APPARATUSES HAVING ENHANCED HEAT TRANSFER ASSEMBLIES**

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G06F 1/20 (2006.01)

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CPC ***H05K 7/20936*** (2013.01); ***G06F 1/20*** (2013.01); ***H01L 23/34*** (2013.01); ***H01L 23/4735*** (2013.01)

(58) **Field of Classification Search**

CPC . H05K 7/20; H05K 7/20309; H05K 7/20936; G06F 1/20; H01L 23/34; H01L 23/473; H01L 23/4735; F28F 3/02; F28F 3/08; F28F 3/14; F28F 7/00; B23P 15/26

USPC 361/679.46, 679.53, 689, 698, 699, 361/702–712, 715, 719, 721, 724; 165/80.2, 80.4, 80.5, 104.33, 104.34, 165/104.26, 185, 166, 908; 257/706–726; 174/15.1, 16.1, 16.3; 62/259.2

See application file for complete search history.

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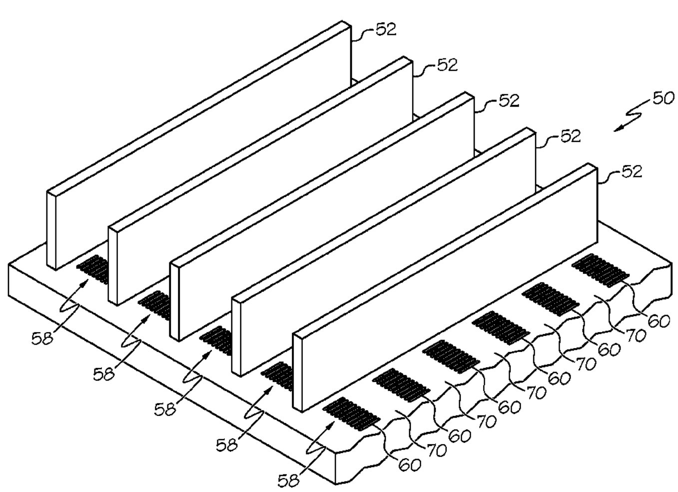
(57) **ABSTRACT**

Enhanced heat transfer assemblies and jet impingement cooling apparatuses having target surfaces with surface fins and microslots are disclosed. In one embodiment, an enhanced heat transfer assembly includes a target surface, a plurality of surface fins extending from the target surface, and a plurality of microslot matrices formed on the target surface. Each microslot matrix includes individual microslots positioned adjacent to each other, and each microslot matrix is adjacent to a jet impingement zone and at least one of the plurality of surface fins. Jet impingement cooling apparatuses and power electronics modules having an enhanced heat transfer assembly with surface fins and matrices of microslots are also disclosed.

20 Claims, 8 Drawing Sheets



(51) **Int. Cl.**
H01L 23/473 (2006.01)
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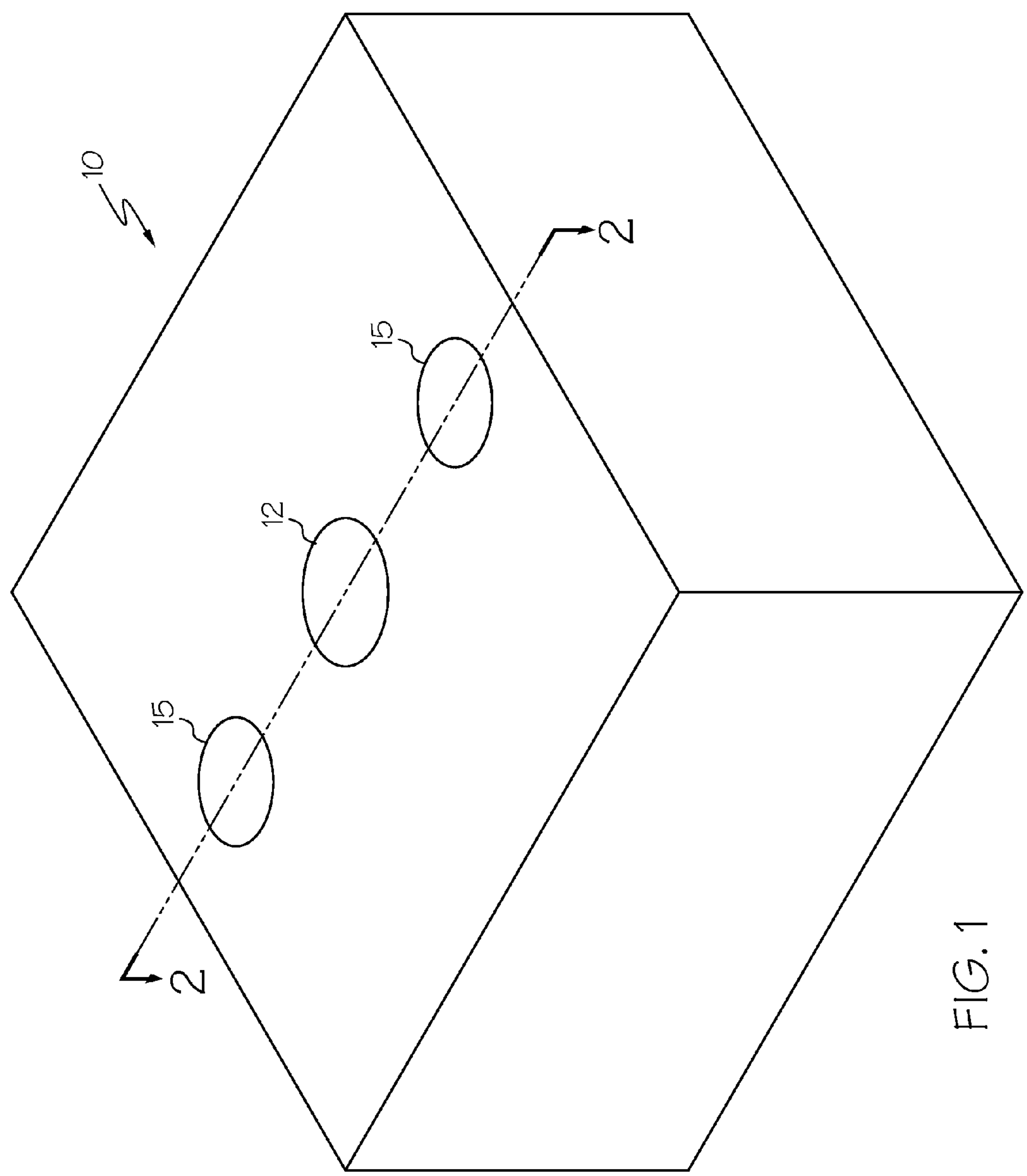

FIG. 1

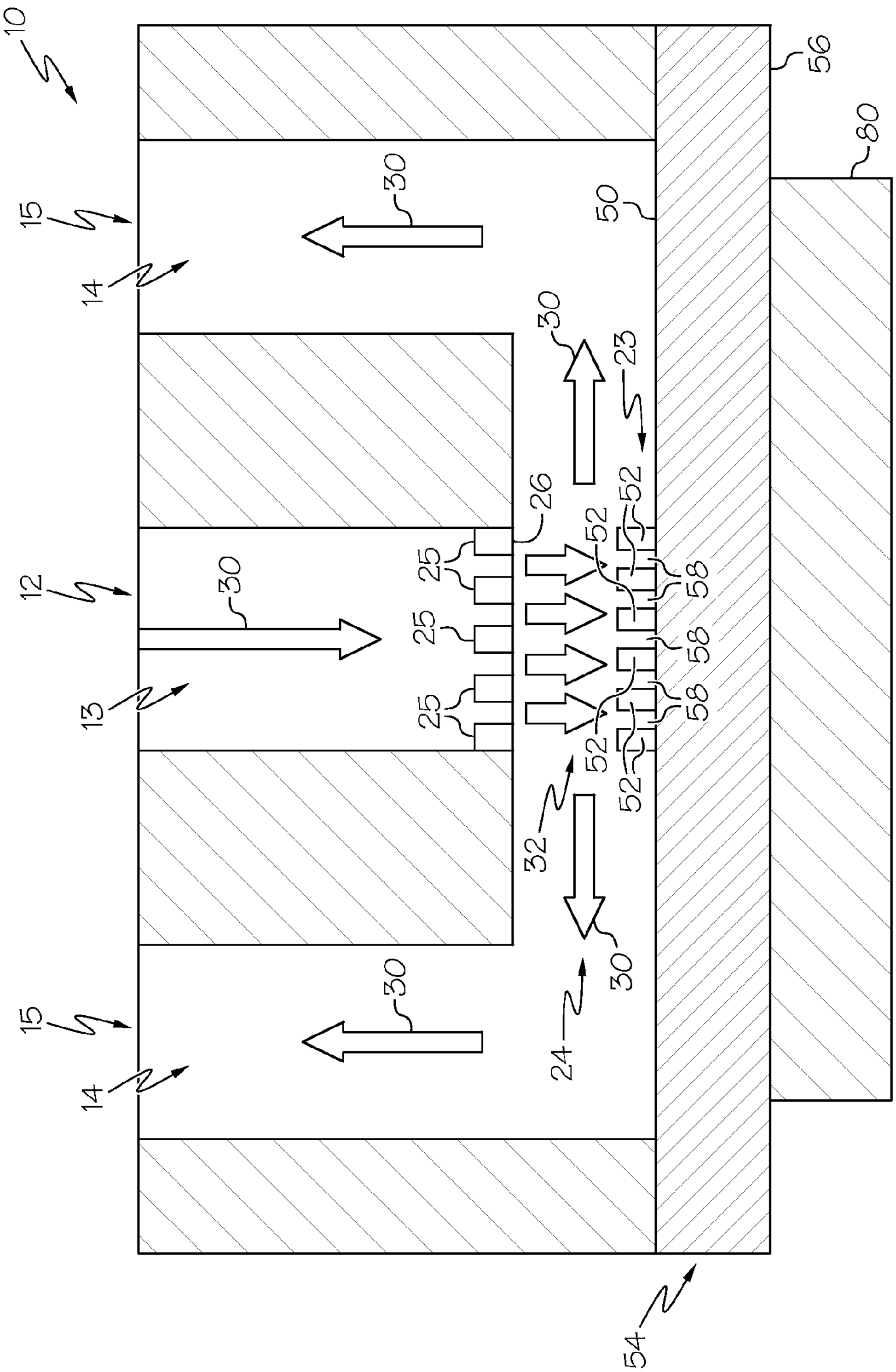

FIG. 2

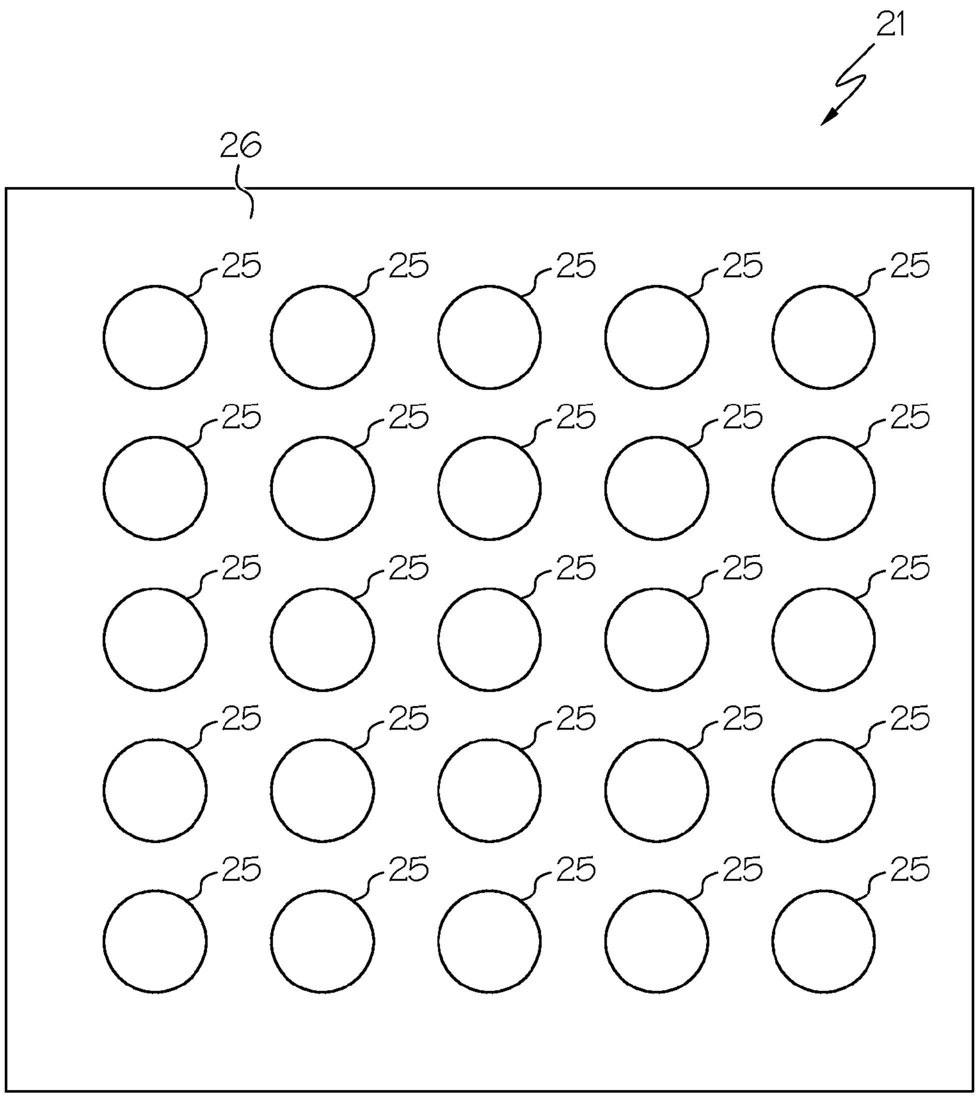
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FIG. 3

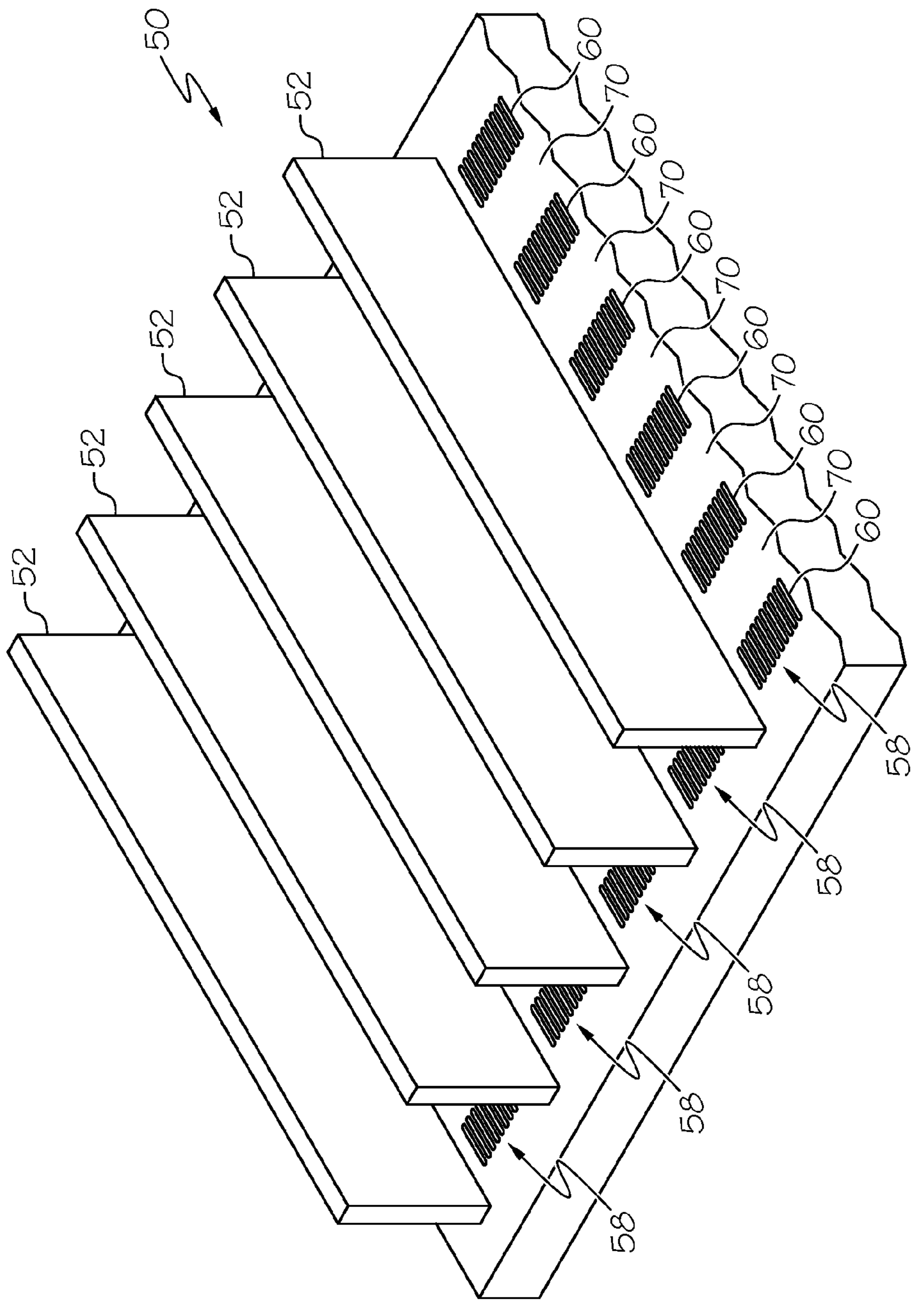

FIG. 4

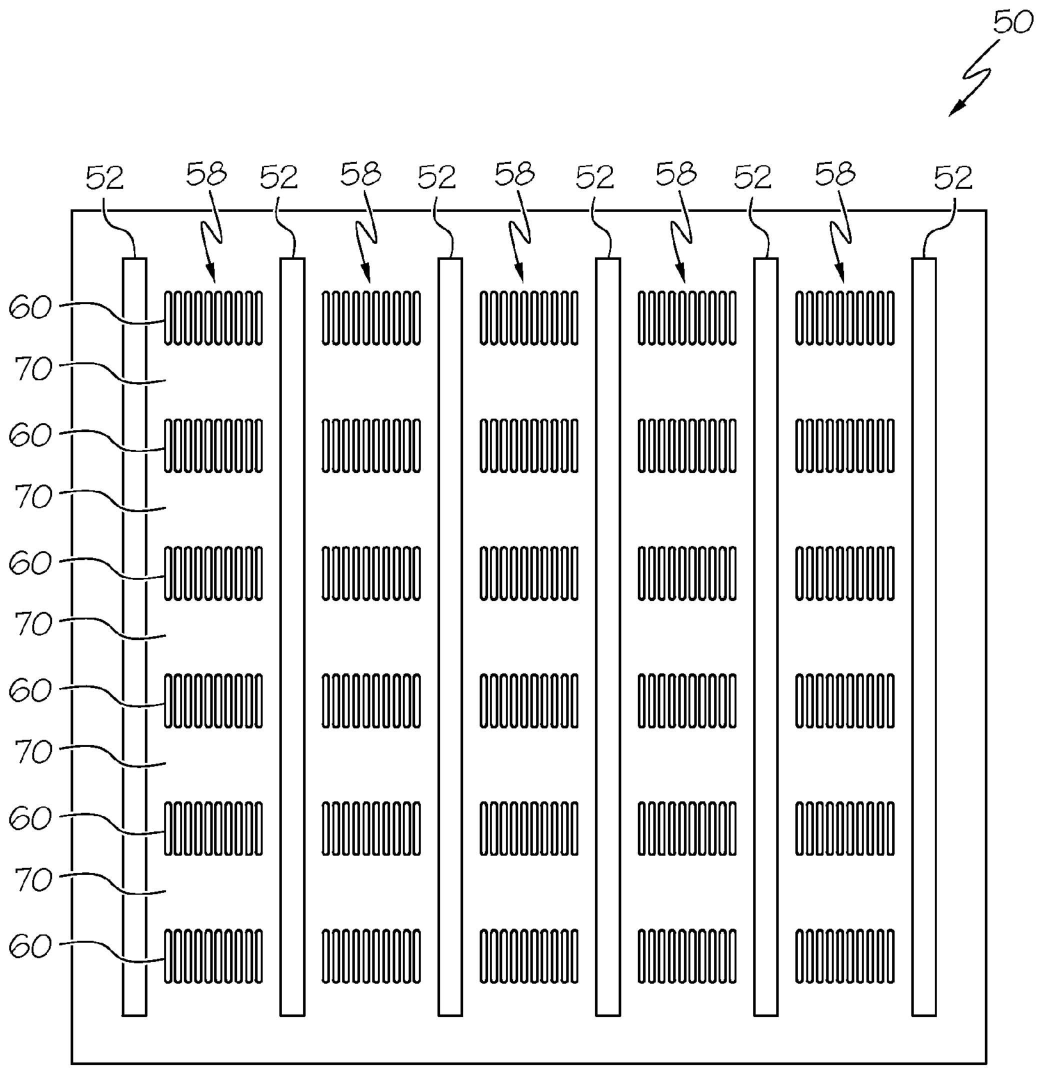

FIG. 5

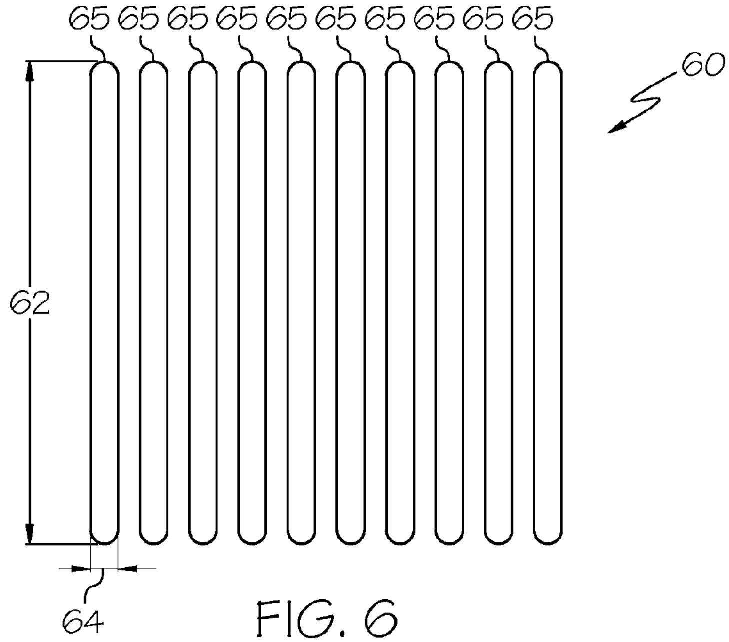

FIG. 6

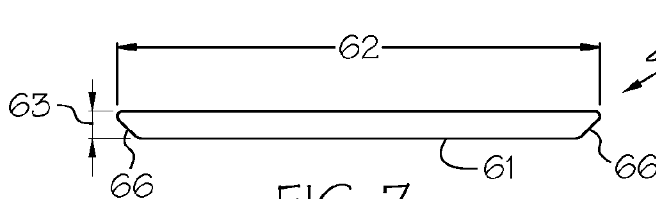

FIG. 7

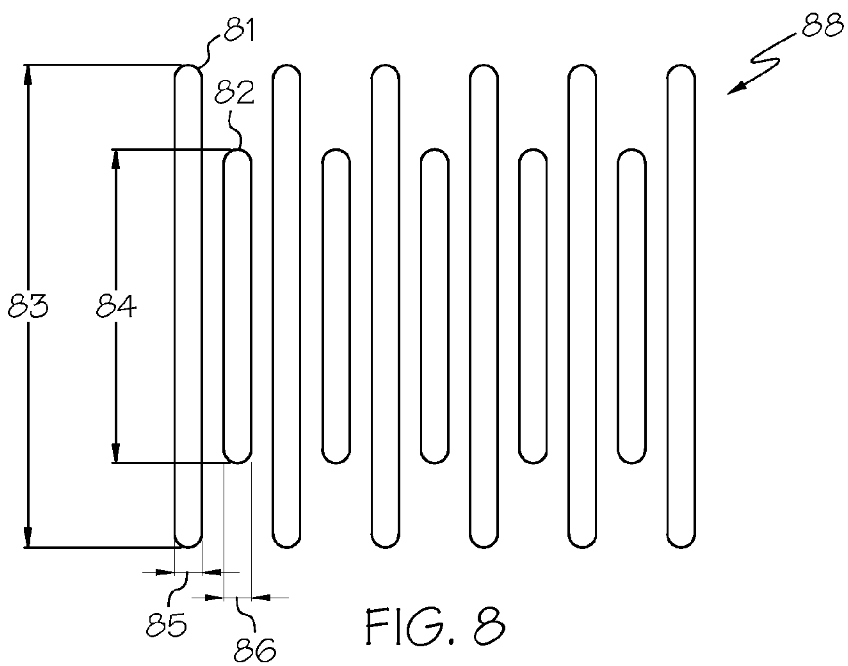

FIG. 8

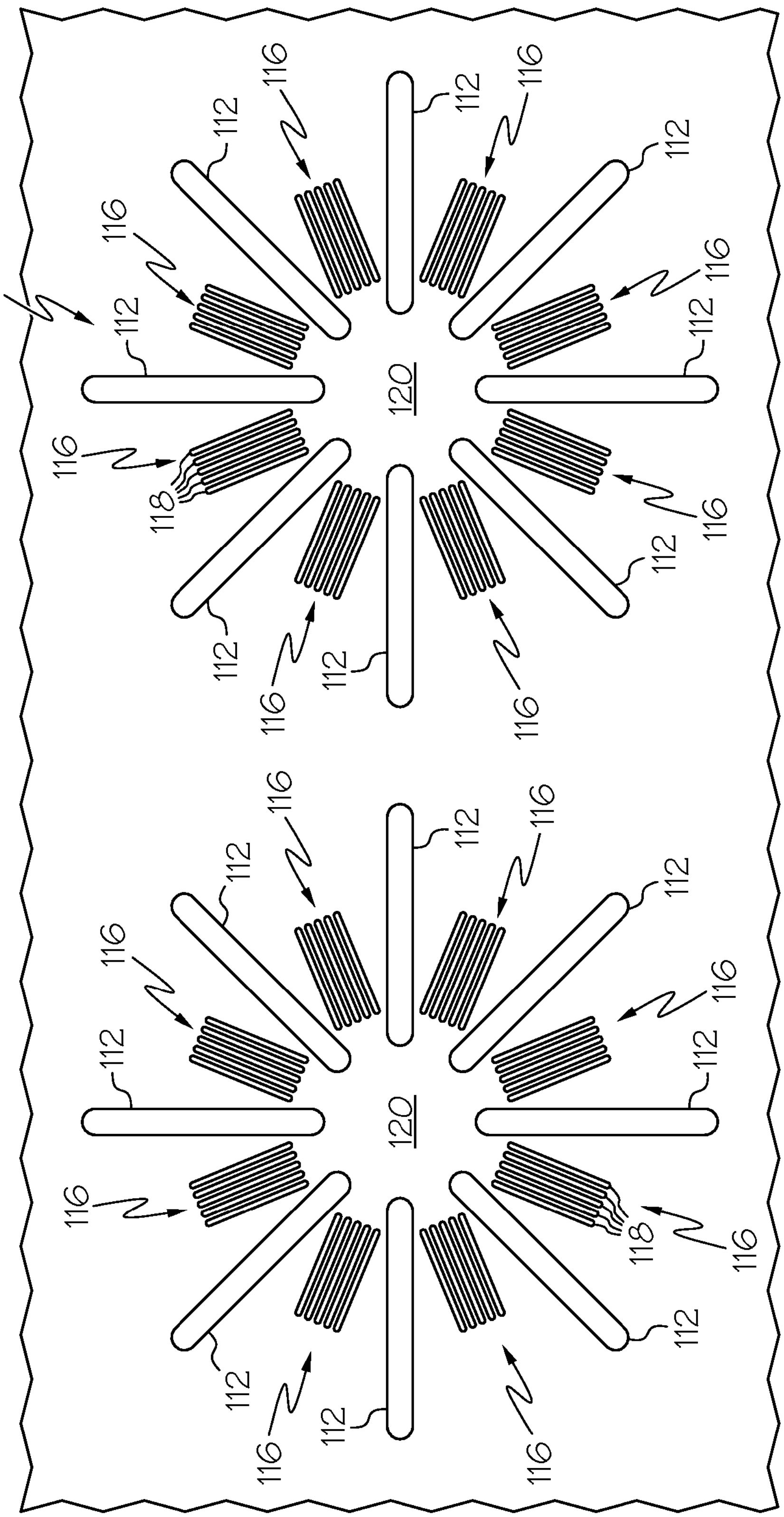

FIG. 9

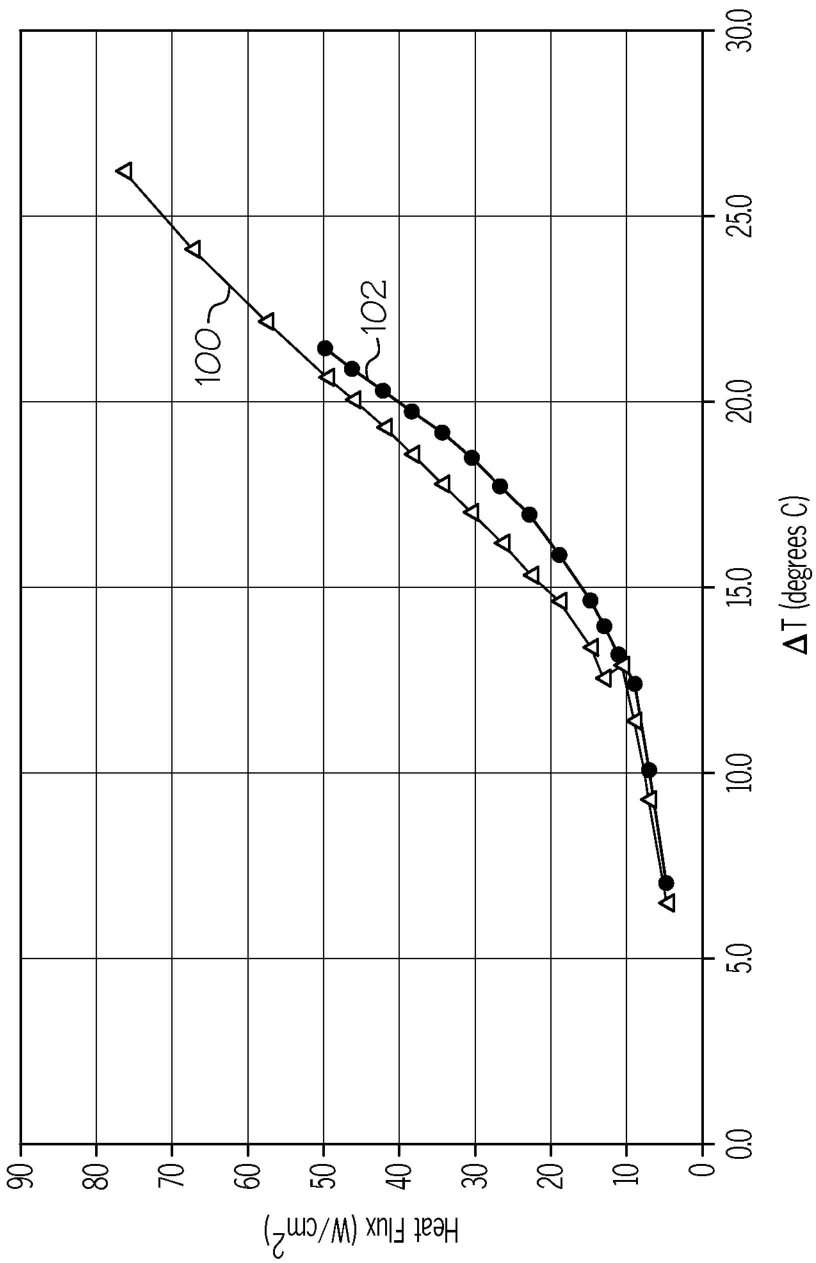
Heat Flux (W/cm^2)
0
10
20
30
40
50
60
70
80
90
ΔT (degrees C)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
100
102

FIG. 10

JET IMPINGEMENT COOLING APPARATUSES HAVING ENHANCED HEAT TRANSFER ASSEMBLIES

TECHNICAL FIELD

The present specification generally relates to cooling apparatuses for cooling heat generating devices and, more particularly, to jet impingement cooling apparatuses having enhanced heat transfer assemblies.

BACKGROUND

Heat generating devices, such as power semiconductor devices, may be coupled to a heat spreader to remove heat and lower the maximum operating temperature of the heat generating device, in some applications, cooling fluid may be used to receive heat generated by the heat generating device via convective thermal transfer, and to remove such heat from the heat generating device. For example, jet impingement may be used to cool a heat generating device by directing impingement jets of coolant fluid onto the heat generating device or a target surface that is thermally coupled to the heat generating device. Additionally, jet impingement may also be combined with two-phase cooling, where the heat generating device is cooled by the phase change of the coolant fluid from a liquid to a vapor. However, in two-phase cooling, stagnant coolant fluid at the target surface that does not change to vapor may adversely affect heat transfer performance.

Accordingly, a need exists for alternative jet impingement cooling apparatuses with increased surface area and/or nucleation sites.

SUMMARY

In one embodiment, an enhanced heat transfer assembly includes a target surface, a plurality of surface fins extending from the target surface, and a plurality of distinct microslot matrices formed on the target surface. Each microslot matrix includes individual microslots positioned adjacent to each other, and each microslot matrix is adjacent to a jet impingement zone and at least one of the plurality of surface fins.

In another embodiment, a cooling apparatus includes a fluid inlet channel, a fluid outlet channel, a jet orifice surface including a plurality of jet orifices fluidly coupled to the fluid inlet channel such that coolant fluid within the fluid inlet channel is capable of flowing through the plurality of jet orifices as a plurality of impingement jets, and an enhanced heat transfer assembly with a target surface. The target surface includes a plurality of surface fins, a plurality of microslot matrices including individual microslots, and a plurality of jet impingement zones on the target surface. Each individual microslot matrix is separated by at least one of the plurality of jet impingement zones and individual matrices. Individual jet impingement zones are disposed between adjacent surface fins and the target surface and the jet orifice surface define an impingement chamber. The plurality of impingement jets are substantially aligned with the plurality of jet impingement zones.

In yet another embodiment, a power electronics module includes a fluid inlet channel, a fluid outlet channel, a jet orifice surface including a plurality of jet orifices fluidly coupled to the fluid inlet channel such that coolant fluid within the fluid inlet channel is capable of flowing through the plurality of jet orifices as a plurality of impingement jets, and a heat transfer assembly including a target surface and a heat transfer surface. The power electronics module further

includes a power electronics device thermally coupled to the heat transfer surface of the heat transfer assembly, wherein the target surface includes a plurality of surface fins, a plurality of microslot matrices including individual microslots, and a plurality of jet impingement zones on the target surface. Each individual microslot matrix is separated by at least one of the plurality of jet impingement zones and individual matrices and individual jet impingement zones are disposed between adjacent surface fins. The target surface and the jet orifice surface define an impingement chamber, and the plurality of impingement jets are substantially aligned with the plurality of jet impingement zones.

These and additional features provided by the embodiments described herein will be more fully understood in view of the following detailed description, in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The embodiments set forth in the drawings are illustrative and exemplary in nature and not intended to limit the subject matter defined by the claims. The following detailed description of the illustrative embodiments can be understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

FIG. **1** schematically depicts a perspective view of a jet impingement, two-phase cooling apparatus according to one or more embodiments described and illustrated herein;

FIG. **2** schematically depicts a cross sectional view of the jet impingement, two-phase cooling apparatus of FIG. **1** according to one or more embodiments described and illustrated herein;

FIG. **3** schematically depicts a top view of a jet orifice plate according to one or more embodiments described and illustrated herein;

FIG. **4** schematically depicts a perspective view of a target surface of an enhanced heat transfer assembly for heat transfer according to one or more embodiments described and illustrated herein;

FIG. **5** schematically depicts a top view of the target surface of FIG. **4** according to one or more embodiments described and illustrated herein;

FIG. **6** schematically depicts a top view of a uniform microslot matrix positioned on the target surface of FIG. **4** according to one or more embodiments described and illustrated herein;

FIG. **7** schematically depicts a cross section view of an individual microslot according to one or more embodiments described and illustrated herein;

FIG. **8** schematically depicts a top view of a non-uniform microslot matrix according to one or more embodiments described and illustrated herein;

FIG. **9** schematically depicts a top view of a target surface having radial surface fins and microslots according to one or more embodiments described and illustrated herein; and

FIG. **10** graphically depicts heat transfer experimental test results using a heat transfer assembly according to one or more embodiments described and illustrated herein.

DETAILED DESCRIPTION

Embodiments of the present disclosure are directed to enhanced heat transfer assemblies and jet impingement cooling apparatuses that may be utilized to cool heat generating devices, such as semiconductor devices. In the embodiments described herein, jet impingement is provided by directing jets of coolant fluid at an impingement region of a target surface, which may be a thermally conductive target plate coupled to a heat generating device. Heat is transferred to the coolant fluid as it flows over the target surface. Upon impinging the target surface, some of the coolant fluid changes phase from a liquid to a vapor thereby further removing heat flux from the heat generating device. Accordingly, embodiments are directed to two-phase, jet impingement cooling devices.

Embodiments described herein may provide for enhanced heat transfer and efficient phase change of coolant fluid. As described in more detail below, coolant fluid impinges the target surface to provide heat transfer. Upon impacting the target surface, heat is transferred to the coolant fluid and some of the coolant fluid changes phase from liquid to vapor. The coolant fluid may change phase from liquid to vapor at nucleation sites located on the target surface. However, the coolant fluid may not efficiently change phase on a smooth surface with limited nucleation sites. Embodiments described herein have enhanced heat transfer assemblies including target surfaces with surface fins and matrices of microslots. The surface fins increase the surface area of the target surface to thereby increase the transfer of heat to the coolant fluid by convective heat transfer. Due to their small size, the matrices of microslots provide additional nucleation sites that are available for boiling the coolant fluid that impinges the target surface. For example, phase change of the coolant fluid may occur at additional nucleation sites provided along the base of the microslots. Various embodiments of cooling apparatuses having enhanced heat transfer assemblies to provide improved heat transfer and additional nucleation sites at the target surface are described in detail below.

Referring now to FIG. **1**, an example jet impingement cooling apparatus **10** is schematically depicted. The cooling apparatus **10** generally includes a fluid inlet **12** and several fluid outlets **15**. The fluid inlet **12** and the fluid outlets **15** may be fluidly coupled to fluid lines (not shown) that are fluidly coupled to a coolant fluid reservoir (not shown). The coolant fluid may be any appropriate liquid, such as deionized water or radiator fluid, for example. The schematically depicted fluid inlet **12** and the fluid outlets **15** may be configured as couplings, such as male or female fluid couplings, for connecting fluid lines to the fluid inlet **12** and the fluid outlets **15**. Coolant fluid flows through fluid inlet **12** and into the cooling apparatus **10**, as described below. After flowing into the cooling apparatus **10**, the coolant fluid may contact a heat transfer assembly and change phase from liquid, to vapor due to heat transfer from the heat transfer assembly to the coolant fluid. The coolant fluid may flow out from the cooling apparatus **10** in vapor form through fluid outlets **15**, as will be discussed in detail herein. Embodiments may have any number of fluid inlets and fluid outlets. Further, although the fluid, inlet **12** is shown in between the fluid outlets **15** in linear form in FIG. **1**, the fluid outlets **15** may be otherwise positioned, such as surrounding the fluid inlet **12** in a circular manner. The fluid inlet **12** and outlets **15** may also take on different shapes, although shown as circular in the illustrated embodiment.

Referring now to FIG. **2**, the exemplary jet impingement cooling apparatus **10** is schematically depicted in cross section along line **2-2** of FIG. **1** according to one embodiment. The fluid inlet **12** is fluidly coupled to a fluid inlet channel **13** and several fluid outlet channels **14** that are fluidly coupled to the one or more fluid outlets **15**. In some embodiments, the fluid outlet channels **14** may converge to a single fluid outlet, and/or exit one or more sides of the cooling apparatus **10** rather than the top as depicted in FIGS. **1** and **2**. In other embodiments, only one fluid outlet **15** is provided.

The fluid inlet channel **13** terminates at a jet orifice plate **21** having a jet orifice surface **26**. FIG. **3** depicts a jet plate **21** according to one embodiment. The jet orifice surface **26** includes a plurality of jet orifices **25**. In the illustrated embodiment, the jet orifices **25** are of uniform diameter and are of circular shape. The jet orifices **25** are also aligned in an array pattern. Although shown in the embodiment of FIG. **3** as a 5×5 array of jet orifices, additional or fewer jet orifices may be included, and patterns other than an array, such as circular, helical, or elliptical patterns may be used. Further, in other embodiments, the jet orifices may have varying diameters, which may allow for modified coolant fluid velocity. Other embodiments may also include jet orifices of different geometry, including rectangular, elliptical, triangular, or other shapes.

Referring again to FIG. **2**, coolant fluid **30** flows through the fluid inlet channel **13** and the array of jet orifices **25**. The coolant fluid **30** exits the jet orifices **25** as impingement jets **32** that impinge a thermally conductive enhanced heat transfer assembly **54** comprising a target surface **50** that is thermally coupled to a heat generating device **80**. (e.g., a semiconductor device) at an interface **56**. The impingement jets **32** may be substantially normal with respect to the target surface **50** in some embodiments. It should be understood that more than one heat generating device **80** may be coupled to the interface **56** of the heat transfer assembly **54**.

As described, in more detail below, the target surface **50** includes thermally conductive surface fins **52** and microslots to further enable heat transfer from the heat generating device to the coolant fluid. The target surface **50** may also be porous or covered in a porous material, which may further enhance heat transfer by providing additional nucleation sites. The target surface **50** may include other surface features as well, such as thermally conductive pins.

Heat generating devices **80** may include, but are not limited to, insulated gate bipolar transistors (IGBT), metal-oxide-semiconductor field, effect transistors (MOSFET), power diodes, power bipolar transistors, and power thyristor devices. As an example and not a limitation, the heat generating device **80** may be included in a power electronic module as a component in an inverter and/or converter circuit used to electrically power high load devices, such as electric motors in electrified vehicles (e.g., hybrid vehicles, plug in hybrid electric vehicles, plug in electric vehicles, and the like).

After impinging the target surface **50**, which may be configured as a plate of thermally conductive material such as copper, tin, or aluminum, for example, the coolant fluid **30** flows away from a general impingement area **23** within an impingement chamber **24** defined by the target surface **50** and the jet orifice surface **26**. Some of the coolant fluid **30** may change phase from a liquid to a vapor due to the high temperature heat generating device **80** being cooled.

FIGS. **4** and **5** depict an exemplary target surface **50** including a plurality of thermally conductive surface fins **52** extending orthogonally from the target surface **50** and impingement regions **58** in perspective and top views, respectively. The impingement regions **58** include microslot matrices **60** and jet impingement zones **70**. For ease of illustration, only one column (or row) of impingement regions **58** is numbered with microslot matrices **60** and jet impingement zones **70**. The impingement jets **32** generally impinge the target surface **50** at impingement regions **58**, or more specifically at the jet impingement zones **70** within the impingement regions **58**, which are adjacent to surface fins **52**.

The surface fins **52** are arranged between rows (or columns) of jet impingement regions **58**. The surface fins **52** may assist in directing the coolant fluid **30** within the impingement chamber **24** shown in FIG. **2**. The surface fins **52** may also enhance thermal transfer by providing additional heat transfer surface area. Although the surface fins **52** are shown as straight fins, other fins may be used, including curvilinear fins or other non-uniform fins. The surface fins **52** may be formed using an abrasive grinding or water jet machining process, an extrusion process, or may be bonded to the target surface. Other fabrication processes may also be used to form the surface fins. Additionally, other embodiments may include surface tins that are non-parallel or of varying dimensions. Pins or posts may also be used instead of or in addition to surface fins.

In the embodiment shown in FIGS. **4** and **5**, the jet impingement zones **70** are positioned such that they are substantially aligned with the jet orifices **25** shown in FIG. **3**. The jet impingement zones **70** generally indicate the portions of the target surface **50** that are initially impinged by the impingement jets **32**. Upon impinging the jet impingement zones **70**, the coolant fluid **30** may flow to the microslot matrices **60** positioned proximate to each jet impingement zone **70**.

The microslot matrices **60** in the embodiment depicted in FIG. **5** are positioned adjacent to the jet impingement zones **70** on one side, and at least one surface fin **52** on another side. The microslot matrices **60** may be uniform across the target surface **50**, or in other embodiments may be non-uniform. For example, the microslot matrices along a perimeter of the target surface may have different dimensions than microslot matrices within an interior portion of the target surface, which may affect coolant fluid flow direction and other fluid properties. Additionally, microslot matrices between jet impingement zones may have varying properties, such as geometry, angular configuration, or dimensions that may be dependent on the impact velocity of the coolant fluid at an adjacent jet impingement region. Although each microslot matrix **60** is shown as being, uniform in FIG. **5**, other embodiments may further implement varying angles, geometry, and/or dimensions to achieve desired heat transfer performance, as described below.

In other embodiments, the layout of the jet impingement zones **70**, surface fins **52**, and microslot matrices **60** may be different from the layout depicted in FIGS. **4** and **5**. The microslot matrices **60** may not be positioned adjacent to surface fins **52**, or the microslot matrices **60** may be positioned within the jet impingement zones **70**. Other embodiments may include microslot matrices positioned adjacent to other microslot matrices and/or jet impingement zones positioned adjacent to other jet impingement zones. Although the microslot matrices **60** are illustrated as being substantially parallel to the surface fins **52**, in other embodiments the microslot matrices **60** may be, for example, perpendicular to the surface fins **52**, or may have an angled configuration with respect to the surface fins **52**. Further, the microslot matrices **60** may be configured as intersecting microslots forming a cross-hatch pattern). Additionally, other embodiments may include jet impingement zones or microslot matrices placed singularly without surface fins positioned adjacent thereto. In yet other embodiments, the target surface may include the jet impingement zones and microslot matrices in a circular, triangular, rectangular, or other pattern rather than in the array pattern shown in FIGS. **4** and **5**. The exemplary target surface **50** shown in FIGS. **4** and **5** may be suited for a cooling apparatus having a 5×5 array of impingement jets, with each jet impinging a single jet impingement zone **70**. Other embodiments may have various configurations with more or fewer impingement jets and the jet impingement zones on the target surface aligned with the impingement jets.

Referring now to FIGS. **6**-**8**, each microslot matrix **60** may be defined by a plurality of individual microslots **65** that are positioned adjacent to each other. FIG. **6** depicts a top view of an exemplary individual microslot matrix **60**. FIG. **7** depicts one individual microslot **65** in cross section. In the illustrated embodiment, the microslot matrix **60** comprises ten individual microslots **65**. It should be understood that other embodiments may include more or fewer microslots in each microslot matrix **60**. In the illustrated embodiment, each microslot **65** has a length **62**, a width **64**, and a depth **63**. Modifying the dimensions of the microslot **65** may affect the amount of surface area created by each microslot **65**. Each microslot further has a base **61** and edges **66**. Each of the individual microslots **65** of the illustrated exemplary microslot matrix **60** is uniform and of linear geometry. In other embodiments, the microslots may be non-uniform and may have varying lengths, widths, depths, or edge geometry. The individual microslots also may have any geometry, such as straight, curved, wavy, or the like.

The edges **66** (i.e., walls) of each microslot **65** may have different shapes, such straight or chamfered as shown in FIG. **7**. For example, rounded edges **66** may allow the coolant fluid **30** to flow in and out of the microslot **65** effectively. The depth **63** and general configuration of the microslots **65** increases the available surface area for heat transfer and phase change of the coolant fluid **30**, which further improves heat transfer.

The microslots **65** may be formed directly on the target surface **50** by a variety of processes. For example, the microslots **65** may be machined with a grinding apparatus directly on the target surface **50**, or a water jet machining process may be used. Laser machining may also be used to form the microslots **65**. Laser machining may provide the finest detail and most precise dimensions for each microslot compared to other processes. Other processes may also be used.

FIG. **8** provides an exemplary alternative embodiment of a microslot matrix **88**. While the microslot matrix **60** shown in FIG. **6** comprises uniform microslots **65**, other embodiments may have non-uniform microslots that define an individual microslot matrix, such as the non-uniform microslot matrix **88** depicted in FIG. **8**. The illustrated non-uniform microslot matrix **88** includes ten individual microslots. A first microslot **81** may have a length **83** and width **85**, and may be positioned adjacent to a second microslot **82** having a different length **84** and width **86**. The remainder of the non-uniform microslot matrix **88** may include additional microslots having the dimensions of the first microslot **81** or the second microslot **82**, or microslots having still other dimensions. In addition, the microslots may have varying depths. Still further, the microslots may be curvilinear or have an arbitrary shape. Individual microslots of the microslot matrix may have different shapes. For example, some of the microslots may be curvilinear while others are linear and/or straight. The microslots may further have varying depths, for example a microslot may be deeper at the edges than the center or may be deeper on one edge than the other.

Upon impinging the target surface **50**, the cooling fluid **30** reaches a localized boiling temperature at nucleation sites provided by the microslots **65** due to the high temperature of the heat generating device being cooled, and therefore phase change of the cooling fluid **30** occurs. Nucleation sites at the microslots may have a lower effective surface energy than other regions of the target surface **50**. The rate of nucleation is dependent, among other factors, upon the number of potential nucleation sites, and accordingly, an increase in the number of potential nucleation sites on the target surface **50** may result in an increased rate of nucleation and therefore increased heat transfer. A target surface with limited nucleation sites may limit the thermal performance of the cooling apparatus **10**. For example, a flat, non-porous target surface may have few nucleation sites, making nucleation inefficient for the impingement jets **32** and may prevent a high rate of nucleation across the target surface.

Due to the geometry and dimensions of the microslots **65**, each microslot **65** provides additional surface area and nucleation sites for nucleation to occur. The nucleation sites may be located along the base **61** of each microslot **65**. The base **61** of each individual microslot **65** may offer a lower effective surface energy and may provide a high density region of nucleation sites for the coolant fluid **30**, aiding in two-phase thermal transfer. The microslots **65** may further guide the coolant fluid **30** to flow along the direction of the microslot **65**, providing capillary assisted flow. Because of this feature, coolant fluid **30** can be directed to various areas of the target surface **50** depending on the orientation, angular configuration, and/or geometry of the individual microslots **65**. Accordingly, the microslots **65** may improve thermal heat transfer by providing additional surface area and nucleation sites for the coolant fluid.

Modifying the dimensions of the microslots may affect the number of nucleation sites and the density of nucleation sites created by the individual microslots. For example, a longer microslot may create additional nucleation sites. Varying the depth of the microslots may also impact heat transfer and may affect the flow of coolant fluid into or away from the microslot. Further, modifying the placement of individual microslots within a microslot matrix may further adjust the heat transfer properties of the target surface. For example, microslots positioned at desired angles may assist in guiding coolant fluid in the angle of the microslot. Additionally, while the microslots shown herein are parallel to each other, in other embodiments the microslots may be transverse to each other. In other embodiments, the microslots may be, for example, arranged in a cross-hatch pattern or may be normal to each other.

Referring now to FIG. **9**, an alternative embodiment of a target surface **110** comprising surface fins **112**, microslot matrices **116**, and jet impingement zones **120** is depicted. In the illustrated embodiment, the target surface **110** includes surface fins **112** that extend radially from each jet impingement zone **120**. Between the surface fins **112** are microslot matrices **116** comprising individual microslots **118**. Although shown with a single microslot matrix **116** between each pair of surface fins **112**, additional microslot matrices **116** may be included, with additional microslot matrices **116** positioned adjacent to the illustrated microslot matrices **116**. The surface fins **112** and microslots **118** in this embodiment of the target surface **110** may incorporate any of the above-discussed characteristics. For example, the surface fins **112** may be curvilinear and of different dimensions, while the individual microslots **118** may also be of different geometries and dimensions, and may also be uniform or non-uniform, as discussed above. This embodiment of the target surface **110** may provide additional surface area due to surface fins **112**, as well as increased surface area and an increased number of nucleation sites due to microslot matrices **116**. The surface fins **112** may also guide coolant as coolant impinges the target surface **110**.

Embodiments of the present disclosure, such as the target surface **50** in FIG. **4**, may increase the rate of nucleation and therefore the heat transfer of the cooling apparatus **10**. By providing surface fins **52** and microslots **65** in microslot matrices **60**, surface area is increased and additional nucleation sites are created, allowing for more effective heat transfer and boiling of the coolant fluid **30**. The position of microslot matrices **60**, as well as the features of individual microslots **65** may be selected based on the size of the target surface **50** and the location of jet impingement zones **70** and surface fins **52** on the target surface **50**, as discussed herein. The enhanced heat transfer assembly **54** described herein having target surface **50** with surface fins **52** and microslot matrices **60** may be implemented into other cooling apparatuses. For example, the enhanced heat transfer assembly, although shown in isolation herein, may be implemented in other two-phase cooling apparatuses or heat transfer apparatus that utilize fluid flow thermodynamics.

EXAMPLES

An experiment was performed comparing the heat transfer of a two-phase heat transfer cooling apparatus using the enhanced heat transfer assembly including the microslot matrices described herein to the same two-phase heat transfer cooling apparatus without microslot matrices. A cooling apparatus with a target surface was operated and the amount of heat transferred from the heat generating device to the coolant fluid in the impingement chamber was measured over time. The same cooling apparatus was then modified to include the microslot matrices as shown in FIGS. **4** and **5** and the experiment was performed again. The amount of heat transferred over time was again measured.

FIG. **10** displays the results of the experiment in a line graph, with heat flux of the device in Watts/cm^2 along the Y-axis and change in temperature between the heat generating device and the coolant fluid at the inlet in degrees Celsius along the X-axis. Both cooling apparatuses utilized target surfaces comprised of copper. Line **100** represents the experimental results of the cooling apparatus with the enhanced heat transfer assembly and line **102** represents the experimental results of the cooling apparatus without the enhanced heat transfer assembly described herein. As shown in the graph, the cooling apparatus with the enhanced heat transfer assembly and target surface including surface fins and microslots provided increased heat transfer. For example, the cooling apparatus with the enhanced heat transfer assembly had a heat flux of approximately 45 Watts/cm^2 with a change in temperature of approximately 20 degrees Celsius, while the cooling apparatus without the enhanced heat transfer assembly had a heat flux of approximately 40 Watts/cm^2 with a change in temperature of approximately 20 degrees Celsius. Thus, the heat transfer performance of the cooling apparatus with the enhanced heat transfer assembly was improved compared to the heat transfer performance of the cooling apparatus without the enhanced heat transfer assembly.

It should now be understood that embodiments described herein are directed to jet impingement cooling apparatuses having target surfaces with surface fins and microslots for enhanced thermal performance. The microslots provide additional nucleation sites and increased surface area for effective and efficient heat transfer from a heat generating device to coolant fluid.

While particular embodiments have been illustrated and described herein, it should be understood that various other changes and modifications may be made without departing from the spirit and scope of the claimed subject matter. Moreover, although various aspects of the claimed subject matter have been described herein, such aspects need not be utilized in combination. It is therefore intended that the appended claims cover all such changes and modifications that are within the scope of the claimed subject matter.

What is claimed is:

1. An enhanced heat transfer assembly comprising:

a target surface;

a plurality of surface fins extending from the target surface; and

a plurality of microslot matrices formed on the target surface wherein:

each microslot matrix comprises individual microslots positioned adjacent to each other, and

each microslot matrix is adjacent to a jet impingement zone and at least one of the plurality of surface fins.

2. The enhanced heat transfer assembly of claim **1**, wherein the individual microslots have a uniform length, a uniform width, and a uniform depth.

3. The enhanced heat transfer assembly of claim **1**, wherein the individual microslots are non-uniform.

4. The enhanced heat transfer assembly of claim **1**, wherein the individual microslots are linear.

5. The enhanced heat transfer assembly of claim **1**, wherein the individual microslots are substantially parallel to the plurality of surface fins.

6. The enhanced heat transfer assembly of claim **1**, wherein the plurality of surface fins is defined by straight surface fins arranged in a radial configuration around the jet impingement zone.

7. The enhanced heat transfer assembly of claim **1**, wherein the target surface is comprised of copper or aluminum.

8. A cooling apparatus comprising:

a fluid inlet channel;

a fluid outlet channel;

a jet orifice surface comprising a plurality of jet orifices fluidly coupled to the fluid inlet channel such that coolant fluid within the fluid inlet channel is capable of flowing through the plurality of jet orifices as a plurality of impingement jets; and

an enhanced heat transfer assembly with a target surface, wherein:

the target surface comprises a plurality of surface fins, a plurality of microslot matrices comprising individual microslots, and a plurality of jet impingement zones on the target surface, wherein each individual microslot matrix is separated by at least one of the plurality of jet impingement zones and individual matrices and individual jet impingement zones are disposed between adjacent surface fins, and

the target surface and the jet orifice surface define an impingement chamber, and the plurality of impingement jets are substantially aligned with the plurality of jet impingement zones.

9. The cooling apparatus of claim **8**, wherein the individual microslots have a uniform length, a uniform width, and a uniform depth.

10. The cooling apparatus of claim **8**, wherein the individual microslots are non-uniform.

11. The cooling apparatus of claim **8**, wherein the individual microslots are linear.

12. The cooling apparatus of claim **8**, wherein the individual microslots are substantially parallel to the plurality of surface fins.

13. The cooling apparatus of claim **8**, wherein the plurality of surface fins is defined by straight surface fins arranged in a radial configuration around individual ones of the plurality of jet impingement zones.

14. The cooling apparatus of claim **8**, wherein the target surface is comprised of copper or aluminum.

15. A power electronics module comprising:

a fluid inlet channel;

a fluid outlet channel;

a jet orifice surface comprising a plurality of jet orifices fluidly coupled to the fluid inlet channel such that coolant fluid within the fluid inlet channel is capable of flowing through the plurality of jet orifices as a plurality of impingement jets;

a heat transfer assembly comprising a target surface and a heat transfer surface;

a power electronics device thermally coupled to the heat transfer surface of the heat transfer assembly, wherein:

the target surface comprises a plurality of surface fins, a plurality of microslot matrices comprising individual microslots, and a plurality of jet impingement zones on the target surface, wherein each individual microslot matrix is separated by at least one of the plurality of jet impingement zones and individual matrices and individual jet impingement zones are disposed between adjacent surface fins, and

the target surface and the jet orifice surface define an impingement chamber, and the plurality of impingement jets are substantially aligned with the plurality of jet impingement zones.

16. The power electronics module of claim **15**, wherein the individual microslots have a uniform length, a uniform width, and a uniform depth.

17. The power electronics module of claim **15**, wherein the individual microslots are non-uniform.

18. The power electronics module of claim **15**, wherein the individual microslots are substantially parallel to the plurality of surface fins.

19. The power electronics module of claim **15**, wherein the plurality of surface fins is defined by straight surface fins arranged in a radial configuration around individual ones of the plurality of jet impingement zones.

20. The power electronics module of claim **15**, wherein the target surface is comprised of copper or aluminum.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 9,131,631 B2
APPLICATION NO. : 13/962303
DATED : September 8, 2015
INVENTOR(S) : Shailesh N. Joshi

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In The Specification

In Column 1, Line 17, delete "," and insert --.--, therefor.

In Column 3, Line 6, insert --,-- after "vapor".

In Column 3, Line 52, delete "," after "the fluid".

In Column 4, Line 37, delete "," after "field".

In Column 5, Line 10, delete "tins" and insert --fins--, therefor.

In Column 5, Line 36, delete "," after "being".

In Column 5, Line 54, insert --(e.g.,-- after "microslots".

Signed and Sealed this
First Day of March, 2016

Michelle K. Lee

Michelle K. Lee
Director of the United States Patent and Trademark Office